Analysis of Hurricane Evacuation Data by Vehicle Classification

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Abstract

Surface transportation is particularly vulnerable to natural disasters, while at the same time is the primary transportation mode for people transportation and for delivering medical supplies, fuel, water, and other essential goods. To better plan for the different categories of vehicles during an evacuation, it is necessary to understand how these vehicles travel during the event and determine if this travel is different considering the vehicle category. The goal of this paper was to investigate the movement of vehicles, by classification, with an emphasis on freight as the consideration of freight in the literature is limited, during hurricane Irma evacuation. This research sought to identify where and when different classes of vehicles were traveling leading up to hurricane landfall and post-storm reentry.

Of the more significant findings, traffic patterns for commercial use vehicles occurred earlier and lasted longer than changes for personal use vehicles. Commercial use vehicles and vehicles for personal use operating in uniquely different ways in an evacuation. Moreover, research results showed that commercial use vehicles may have underutilized rest and this suggests that truckers are driving longer distances and possibly longer hours before hurricanes. This paper may serve as the foundation for future research into vehicle classification analysis during emergency events and will hopefully lead to the inclusion of commercial use versus personal vehicles in evacuation planning.

Keywords: Hurricane, Irma, Vehicle Categories, Evacuation, Florida

1. Introduction

As the number of emergency events throughout the world increase, there is an enhanced need to understand mass evacuations. To better plan for commercial vehicles during an evacuation, it is necessary to understand how these vehicles travel during the event and determine if this travel is different from the general public. The goal of this paper was to investigate the movement of vehicles, by classification, with an emphasis on hurricane Irma evacuation. This research sought to identify where and when different classes of vehicles were traveling leading up to hurricane landfall and post-storm reentry. Furthermore, the investigation used Florida statewide continuous-count-station traffic volumes, by vehicle classification, from 2017 and 2018. Traffic volumes for each class were then compared between years, to identify locations where traffic was moving differently during the evacuation. The data was then used to identify days on which, traffic was significantly different between years.

Hurricane Irma had been referred to as the largest evacuation in the history of the United States. The storm's path and "cone-of-uncertainty" encompassed nearly the entire state of Florida [1] and resulted in approximately 6.5 million Floridians being placed under either mandatory or voluntary evacuation orders [2]. Ultimately, Irma made two landfalls on September 10, 2017, the first on Cudjoe Key in the lower Florida Keys at approximately 9:10 AM and the second near Marco Island, just south of Naples, FL at approximately 3:35 PM [3]. The storm left 65 percent of homes without power statewide [4] and the lower Florida Keys remained closed to non-residents for approximately three weeks following landfall [5]. The National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI) estimates that wind and water damage caused by Irma totaled between $37.5 to $62.5 billion USD, making Irma the fifth-costliest hurricane in US history [6].

The goal of an evacuation is to avoid injuries, loss of life and, to a lesser extent, property damage and economic loss. Thus, a primary objective is to move all evacuees outside of a threat area as safely and as quickly as possible [7]. Evacuation route planning (ERP) is an important component of emergency management that seeks to minimize the loss of life or harm to the public during natural disasters or terrorist attacks [8]. Important tasks during an evacuation are ensuring employee safety, supporting local community health, maintaining customer relationships, identifying strategy actions, and improving supply chain resilience. A well-organized logistics strategy can increase the system and supply chain resilience by helping with faster recovery [9].

Analysing traffic data from detectors is a methodology applied to a variety of natural disasters. For instance, Chang et al. used traffic data to analyse the restoration of the highway system and recovery after the Kobe earthquake [10]. Wolshon used detector data from Louisiana collected during Hurricane Katrina to assess how well the maximum capacities suggested by the Highway Capacity Manual matched the detector reported flows for different types of roadways [11]. These roadway types included freeways operating in the normal direction, contraflow freeway segments, four-lane arterial roadways, and two-lane arterials. Another worth mentioned work was the temporal-spatial analysis of hurricane Katrina evacuation [12] that summarized the evacuation across roadway infrastructure. Archibald et al. (2012) used traffic data from automated traffic counters to explore traffic patterns before, during and after an evacuation to investigate the behaviour of residents and visitors [13]. The results of the analysis suggest that that in the case of Hurricane Irene in Delaware, the evacuation orders were effective, provided sufficient lead time, and reached the intended audience. Traffic count data were also used by Li et al. [14] to develop empirical response curves for Hurricane Irene for a single county in New Jersey. They also identified evacuation volumes and compared these to the volumes from the previous week.

2. Methodology

The methodology of the research was divided into three phases: data collection and management, spatial analysis, and temporal comparisons. Data collection and management obtained continuous-count-station data from the state of Florida for both 2017 and 2018, by vehicle classification. The data were then processed into a manageable format. The second phase used geographic information systems (GIS) to display where and when traffic varied across the state. The third and final phase was a quantitative investigation into which vehicle classifications were statistically different and on which dates, statewide. This phase used a two-sample, two-tailed t-test to compare sensor volume, by classification, on similar days, between years. Overall increases in freight movement between years prevented a more precise paired analysis.

2.1 Data Collection and Management

As part of the National Highway Performance Monitoring System (HPMS), the Federal Highway Administration (FHWA) regulates state departments of transportation to submit annual traffic statistics [8]. State transportation agencies build, operate, and maintain permanent traffic monitoring stations to collect, among other measures, traffic count information. Referred to as continuous-count-stations, these traffic count detectors report hourly traffic counts continuously throughout the year, year-over-year, to meet the federal regulation requirement. Data for this research was provided by the Florida Department of Transportation (FDOT) from 230 continuous count stations located throughout the state (see Fig. 1). The analyzed traffic data were from August, September, and October both in 2017 and 2018. FDOT provided hourly traffic volumes for each of the 13 FHWA vehicle classifications categories [15]. Broadly, this research compared vehicle movements between years for similar days, i.e. the first Monday in September 2017 was compared to the first Monday in September 2018. Furthermore, this research investigated categories **2** (Passenger Cars), **3** (Four tires, single unit, vans), **5** (Two axles, six tires, single unit), **8** (Four or less axle, single trailer), and **9** (Five axel tractor semitrailer), which accounted for over 96 percent of all traffic during the analysis years. In contrast, each of the categories not investigated (1, 4, 6, 7, 10, 11, 12, 13) individually constituted less than one percent of the daily traffic. Additionally, two broader groups of vehicles were identified in the study: vehicles for personal use, which included categories 2 and 3; and vehicles for commercial use, categories 5, 8, and 9.

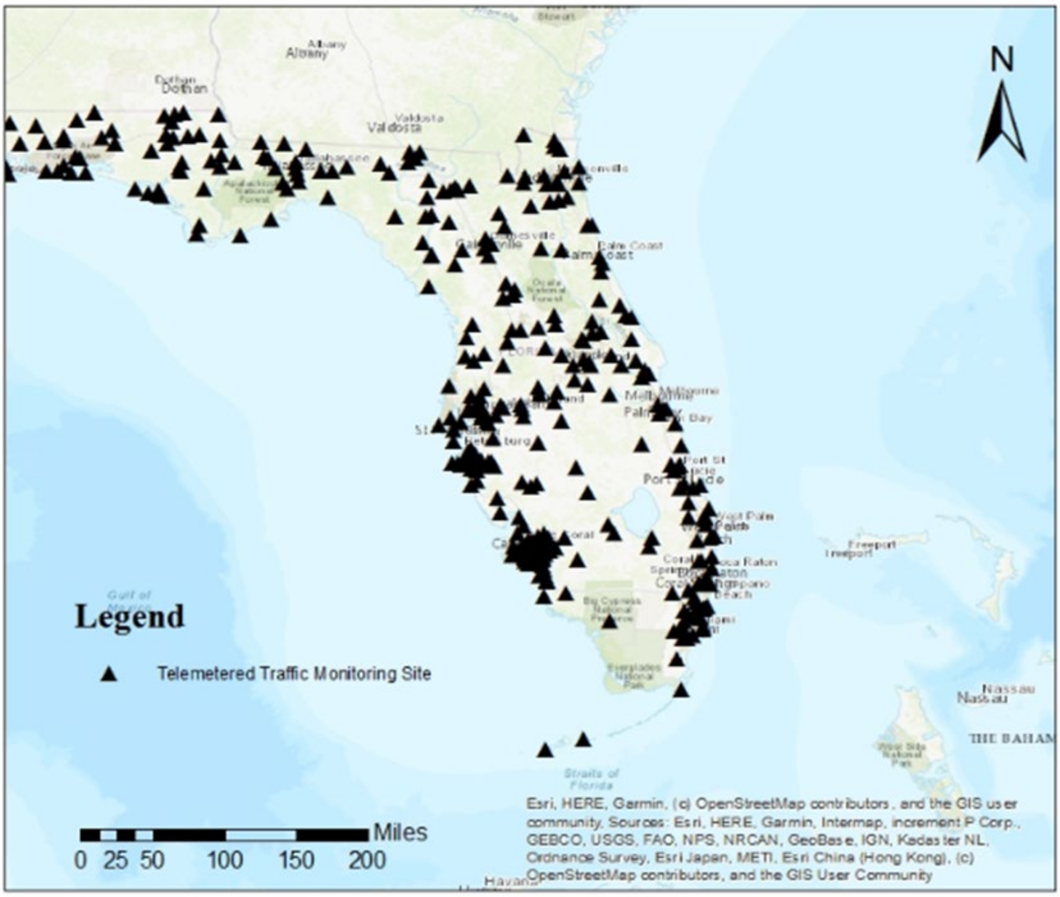

Figure 1. Telemetered Traffic Monitoring Site in Florida State

2.2 Spatial Analysis

The spatial analysis was conducted at the state level by investigating the difference in detector volumes for similar days between years. A geographic information system (ArcGIS) was used to project this data onto a base map for visual comparison. The spatial analysis applied to the movement of vehicles for personal use and the movement of vehicles for commercial use, but not to the individual vehicle categories. The spatial comparison was conducted in accordance with **Equation 1:**

$$u_i = u_{i,a}^{t_2} - u_{i,a}^{t_1} \tag{1}$$

Where: u_i is the difference in total daily traffic at location i, between years t_2 (2018) and t_1 (2017) on day a.

The difference in volume calculated in Equation 1 was projected onto a base map and spatially weighted to generate a raster image for the creation of spatial heat maps. A spatial heat map is a data visualization technique to represent the density of geographic features. Inverse Distance Weighting (IDW) was used to interpolate the volumes between data sensor locations. The IDW is a multivariate interpolation and the value for each location was calculated based on **Equation 2**:

$$u(x) = \begin{cases} \frac{\sum_{i=1}^{N} w_i(x) u_i}{\sum_{i=1}^{N} w_i(x)} & if\ d(x, x_i) \neq 0\ for\ all\ i \\ u_i & if\ d(x, x_i) \neq 0\ for\ all\ i \end{cases} \tag{2}$$

Where u was the interpolation value for location x, $u_i = u(x_i)$ was the samples for $i = 1,2, \dots, N$ and N was the total number of detectors. Also, weights were different for each location based on distance d between the detectors and the points in the p represented the power parameter and was calculated with **Equation 3**.

$$w_i(x) = \frac{1}{d(x, x_i)^p} \tag{3}$$

2.3 Temporal Comparison

To determine when the traffic pattern changed leading up to the evacuation and hurricane landfall, a t-test was conducted of the 202 detectors, for each day. Using an independent, two-tailed student t-test, total daily traffic volumes at each detector were compared for similar days between years. Days were considered significantly different when the critical t-scores resulted in p-values less than 0.05. Overall, during the three month investigation period, Aug, Sept., and Oct. 2018 saw a 19 million-vehicle increase over the same period in 2017 for vehicle categories 2 and 3. Whereas categories 5, 8 and 9 saw a surge of nearly 1 million vehicles in 2018 during this same period. As a result, the two datasets were considered as unique and independent events. The two tail independent t-test used **Equation 4** and **Equation 5:**

$$t_a = \frac{\overline{u_{a,t_2}} - \overline{u_{a,t_1}}}{\sqrt{\frac{s_a^2}{N_{a,t_2}} + \frac{s_a^2}{N_{a,t_1}}}} \tag{4}$$

$$s_a^2 = \frac{\sum(u_i - \overline{u_{a,t_2}})^2 + \sum(u_i - \overline{u_{a,t_1}})^2}{N_{a,t_2} + N_{a,t_1} - 2} \tag{5}$$

$\overline{u_{a,t_2}}$: represents the mean value from 2018 dataset in day a, $\overline{u_{a,t_1}}$: represents the mean value from 2017 dataset in day a, s_a^2 : is an estimator of the pooled variance of two groups, N_{a,t_2}: represent the size of 2018 dataset in day a, N_{a,t_1}: represent the size of 2017 dataset in day a

3. Analysis and Results

The multi-level analysis revealed that the effect of a hurricane on transportation started 2-3 days before landfall and return to pre-storm levels after 3-4 days. Significant differences in volumes were observed on landfall days across all vehicle classifications. In the **Figure 2** we can observe the track of hurricane Irma.

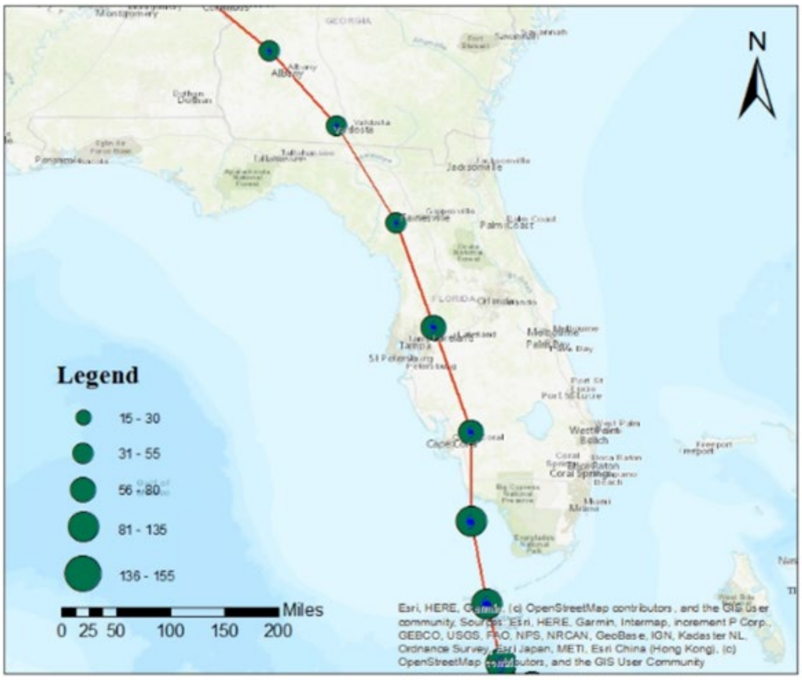

Figure 2 Landfall of Hurricane Irma in Florida State

3.1 Spatial Analysis

The results from IDW were presented in 2 figures were divided into personal use vehicles (categories 2 and 3) and commercial use vehicles (category 5, 8, and 9). These two figures each show eight consecutive days of traffic, encompassing landfall. These days were selected after examining all days in the dataset and determining this eight-day window approximately encompasses the storm events. The low values represent locations where the number of cars was more in 2017 compared to 2018 and the high-value locations are where the volumes were higher in 2018. Therefore, brown/red colors signify more cars in 2017, whereas blue colors represent more cars in 2018. **Figure 3** shows personal use vehicles (categories 2 and 3) beginning Thursday, September 7, 2017, through Thursday, September 14, 2017. This period of traffic is compared to Thursday, September 6, 2018, through Thursday, September 13, 2018. During the first two days of the analysis period (**Figure 3 (a)**) and **Figure 3 (b)**), the number of personal use vehicles began to increase across the state and traffic appeared to be moving from South to North. However, small areas encompassing high population cities did see some instances where traffic was greater in 2018. The day before landfall, September 9, 2017 (**Figure 3 (c)**), traffic levels were substantially higher in 2017, hurricane Irma year. Traffic appears to increase yet again on September 10 (landfall) and the following day (**Figure 3 (d)** and **Figure 3 (e)**). This increase likely signifies the start of the evacuation reentry. Two days after landfall (**Figure 3 (f)**), small areas in the southeast were observed to have fewer trips in 2017 than in 2018 (indicated by the blue regions). This trend continued for the next two days until a general return to pre-storm levels on September 14, 2017 (**Figure 3 (h)**). Evacuation orders for hurricane Irma generated a remarkable number of trips for personal use vehicles. It appears vehicles were generated from nearly every region of the state and were generally traveling north. The figure suggests changes in traffic between years for South Florida, was less severe and returned to pre-evacuation values sooner than other regions. The investigation also suggests that people started reentry as soon as possible, beginning on the same day as landfall. Finally, while the maps have a smooth surface, some areas stand out. In the North, regions with darker shading suggest these locations experienced more vehicles in 2017, while lighter shading was seen in the south and center of the state, suggesting more vehicles in 2018. These locations may distinguish rest areas. It appears that drivers chose not to use these areas with some exceptions near the state borders.

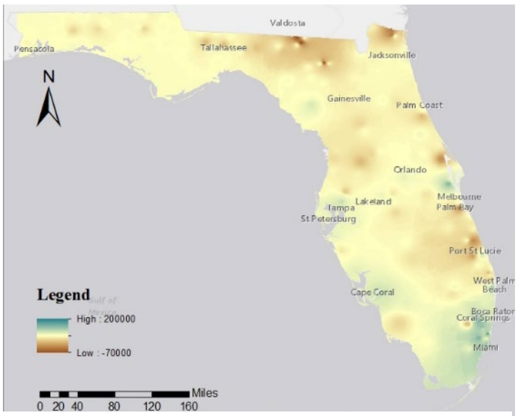

Figure 3 (a) Personal Use Vehicles, 9/7/17

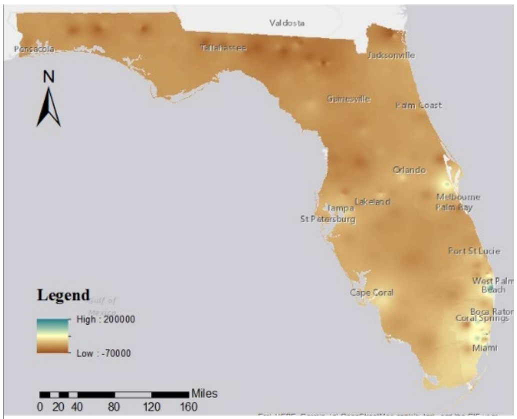

Figure 3 (b) Personal Use Vehicles, 9/8/17

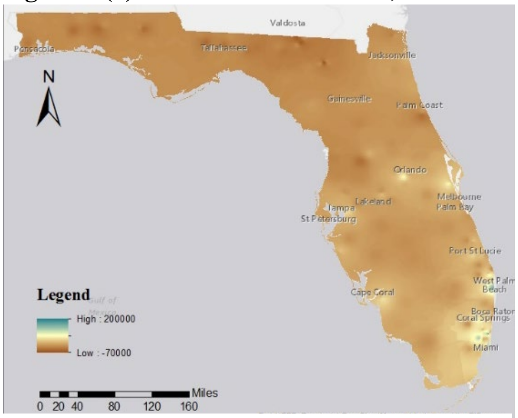

Figure 3 (c) Personal Use Vehicles, 9/9/17

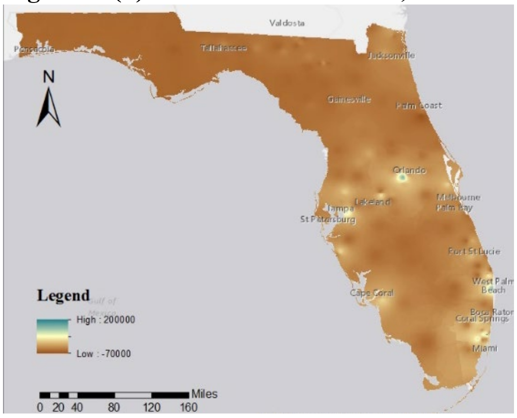

Figure 3 (d) Personal Use Vehicles, 9/10/17

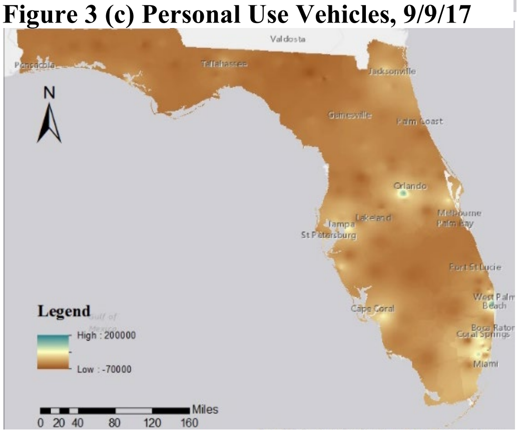

Figure 3 (e) Personal Use Vehicles, 9/11/17

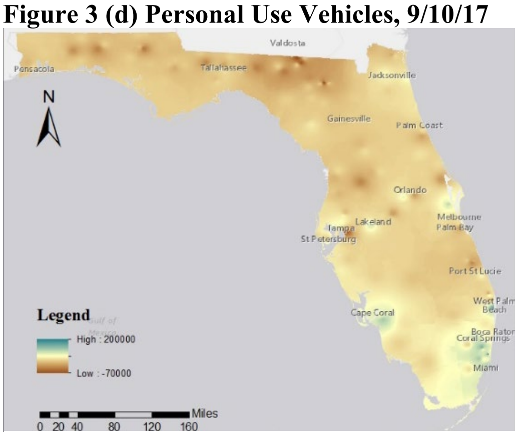

Figure 3 (f) Personal Use Vehicles, 9/12/17

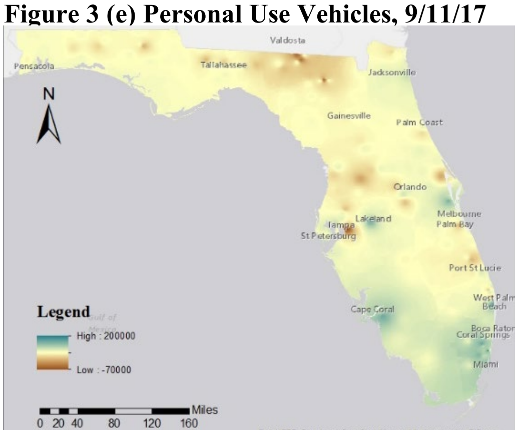

Figure 3 (g) Personal Use Vehicles, 9/13/17

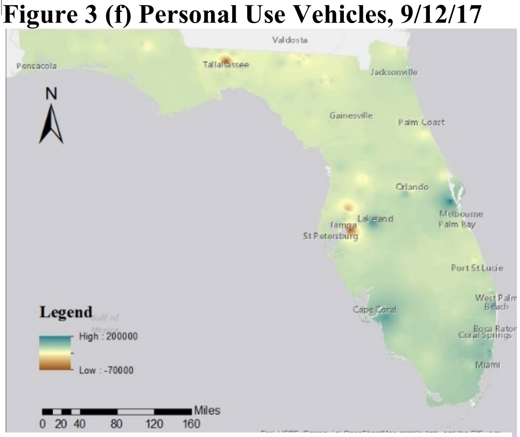

Figure 3 (h) Personal Use Vehicles, 9/14/17

Figure 4 shows commercial use vehicles (categories 5, 8, and 9) beginning Thursday, September 7, 2017, through Thursday, September 14, 2017. This period of traffic is compared to Thursday, September 6, 2018, through Thursday, September 13, 2018, based on. The first day of the analysis, September 7, 2017, shown in **Figure 4 (a)**, suggests truck traffic was generally equivalent between years across the state, with slightly more trucks operating around cities in 2018. The northern portion of the state does show some regions where truck traffic was elevated in 2017 on this day. The following day, truck traffic in the north begins to increase, while truck traffic around rest areas and major population centers in the south, slow. This trend continues on September 9 (**Figure 4 (c)**), the day before landfall. On September 10, 2017, Hurricane Irma made landfall, and the movement of trucks was higher in 2017 comparatively. Rest areas in Florida consist of the only locations where truck traffic was higher in 2018. This may suggest these areas were underutilized or probably closed. Increased truck volumes for 2017 were also noticed the following day (**Figure 4 (e)**) with a similar rest area pattern. By September 12, (**Figure 4 (f)**), truck traffic begins to decrease in the south and central parts of the state but is still elevated in the northern region. Finally, on the last two days of the analysis period, truck traffic in 2018 dominates the figures as the region begins to return to pre-storm levels.

Overall, the results suggest that truck movement was strongly correlated with the evacuation orders. The number of trips was increased before the evacuation in the direction from South to North and peaking on landfall day. After which, truck traffic starts to decrease following the opposite direction from North to South. Exceptions to this were seen near rest areas, which saw more trucks in 2018.

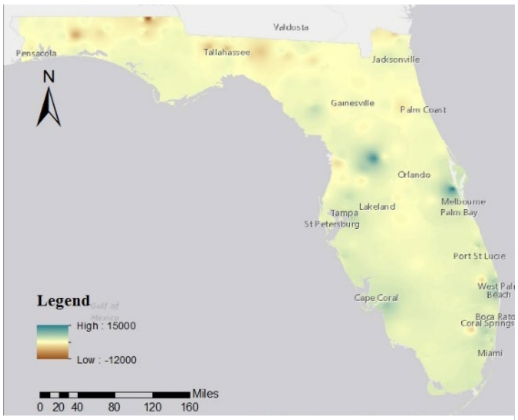

Figure 4 (a) Commercial Use, 9/7/17

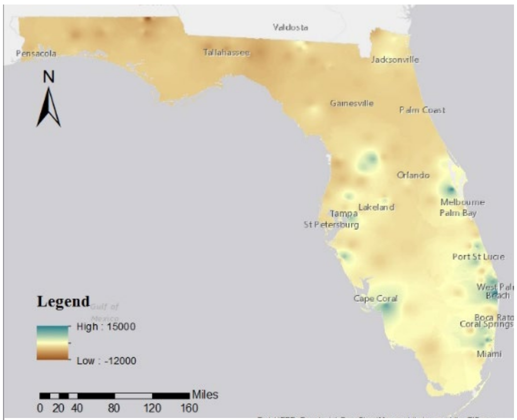

Figure 4 (b) Commercial Use, 9/8/17

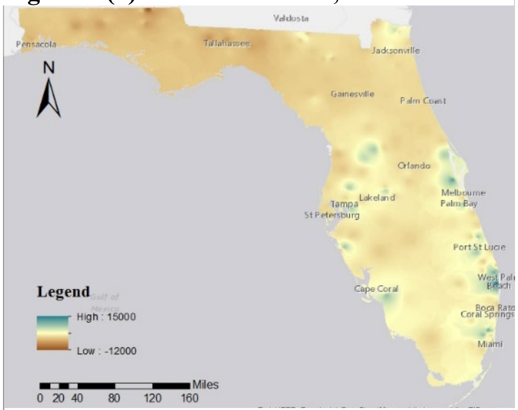

Figure 4 (c) Commercial Use, 9/9/17

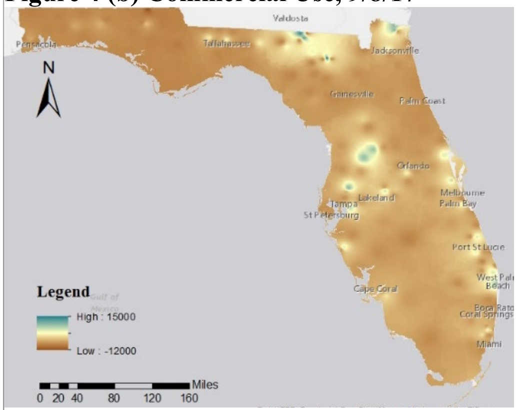

Figure 4 (d) Commercial Use, 9/10/17

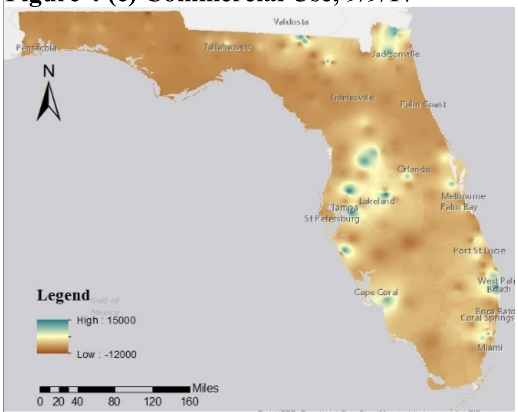

Figure 4 (e) Commercial Use, 9/11/17

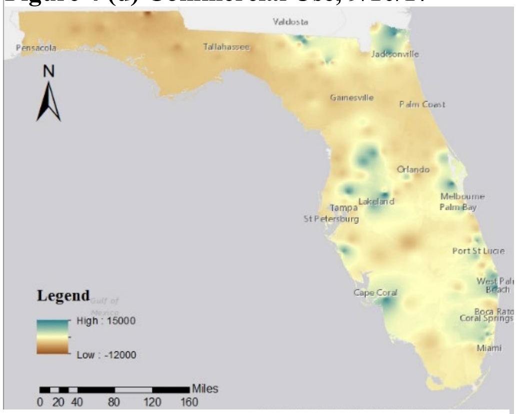

Figure 4 (f) Commercial Use, 9/12/17

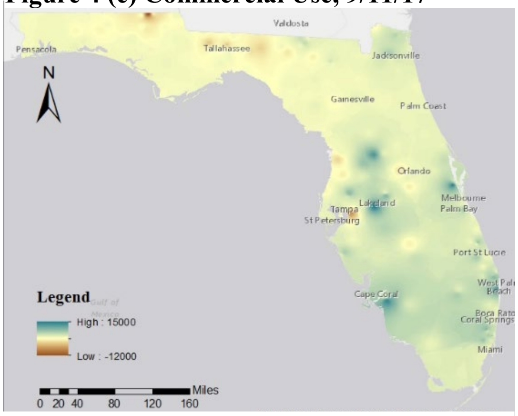

Figure 4 (g) Commercial Use, 9/13/17

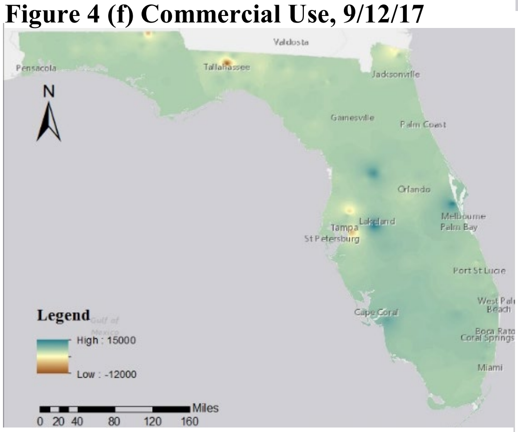

Figure 4 (h) Commercial Use, 9/14/17

3.2 Temporal Analysis

The temporal analysis compared traffic volumes between years using an independent t-test of total daily traffic at each detector for similar days. For the analysis of Hurricane Irma, 202 (N=202) detectors statewide were investigated. **Table 1** provides the t-test p-value results for eight days encompassing Hurricane Irma's landfall. The first column shows the analysis date in 2017, followed by their complementary dates in 2018. Then the table provides a comparison of personal use vehicles (classification 2 and 3 combined) and then commercial use vehicles (classifications 5, 8, and 9 combined). The table then shows the t-test results of each vehicle classification, independently. Personal use vehicle travel was significantly different on September 9-11, 2017, representing the day before, day of, and day after Irma's landfall. Hurricane Irma's impact on commercial use vehicles, however, began earlier and lasted longer. Commercial use vehicle travel was significantly different for the period of September 8-12, 2017. Vehicle classification 8 was significantly different on September 8, but not on September 9. Whereas classifications 5, 8, and 9 were different on September 8. Between the periods of September 9-11, all travel was significantly different between years, regardless of classification. By September 12, only classification 9 was significantly different and by September 13, 2017, traffic was indistinguishable from 2018 levels.

Table 1 P-values for hurricane Irma in Florida

2017	*2018*	*Class. 2 & 3*	*Class. 5 & 8 & 9*	*Class. 2*	*Class. 3*	*Class. 5*	*Class. 8*	*Class. 9*
9/7	9/6	0.400	0.960	0.400	0.800	0.800	**0.020** [a]	0.700
9/8	9/7	0.090	**0.012** [a]	0.100	**0.030** [a]	**0.005** [a]	0.600	**0.010** [a]
9/9	9/8	**0.000**[a]	**0.000** [a]	**0.000** [a]	**0.000** [a]	**0.003** [a]	**0.008** [a]	**0.000** [a]
9/10	9/9	**0.000** [a]	**0.000** [a]	**0.000** [a]	**0.000** [a]	**0.000** [a]	**0.000** [a]	**0.000** [a]
9/11	9/10	**0.000** [a]	**0.000** [a]	**0.000** [a]	**0.000** [a]	**0.000** [a]	**0.000** [a]	**0.000** [a]
9/12	9/11	0.480	**0.000** [a]	0.600	0.200	0.100	0.300	**0.000** [a]
9/13	9/12	0.910	0.300	0.990	0.600	0.700	0.600	0.100
9/14	9/13	0.670	0.910	0.700	0.600	0.900	0.500	0.990

4. Discussion

This section discusses some of the limitations of the research that should be considered alongside the research results. One of the more significant limitations was data coverage. Data coverage was restricted to FDOT detectors that were in operation during both 2017 and 2018. FDOT detectors were generally located near areas of high population. Rural areas may therefore be underrepresented in the sample. Furthermore, this study investigated total daily traffic between years and did not consider hourly fluctuations. By aggregating the data by time, it was possible to investigate and present travel patterns over longer periods. However, this aggregation prevented a more detailed investigation into departure and return times. Prior research has found that evacuees prefer morning departures [16]. The aggregation of data into 24-hour periods prevented an investigation into this phenomenon. Likewise, because of the 24-hour aggregation, evacuees departing on landfall day were indistinguishable from those returning afterward. The analysis also did not consider the direction of travel. By investigating sites as a whole (instead of by direction), it permitted a statewide analysis of both the evacuation and reentry. However, it did prevent an investigation into where vehicles were traveling and on which days.

5. Conclusions

The need for effective evacuation plans is critical. While the literature on auto-based evacuations for regional hurricanes is extensive, the consideration of vehicle categories separately during an emergency is not extensively analyzed. This study represents one of the first empirical investigations into the movement of different vehicle categories before, during, and after an evacuation event. This paper may also serve as the foundation for future research into commercial travel during evacuations and will hopefully lead to the inclusion of commercial use vehicles in evacuation planning.

Of the more significant findings, of this research was that changes in traffic patterns for commercial use vehicles occurred earlier and lasted longer than changes for personal use vehicles. In a very practical sense, commercial vehicles were reacting to the approaching storm differently. This finding suggests that freight vehicles' purpose impacts their travel patterns in an emergency period. It would then stand to reason that if these two system users are operating in uniquely different ways during the evacuation, then commercial drivers should have evacuation plans tailored to meet their transportation requirements.

Another significant finding identify that South Florida was less severe and returned to pre-evacuation values sooner than other regions. Moreover, the high number of trips during landfall day suggested that people started reentry as soon as possible, beginning on the same day as landfall. Finally, evacuees preferred to drive long hours to get away from the restricted area compared to making stops close to the borders.

Future research could investigate why commercial driving patterns were different from that of personal use vehicles and how evacuation planners could better accommodate their needs. After landfall, the need for utility vehicles and other large vehicles is generally necessary to facilitate the recovery effort. Finally, given the devastation caused by the category 5 hurricane, it is likely these trucks represented utility and debris removal vehicles.

Acknowledgment

Funding for this research was provided by the Freight Mobility Research Institute located at Florida Atlantic University; a United States Department of Transportation, University Transportation Center. The authors would also like to thank Joey Gordon of the Florida Department of Transportation for his assistance in providing the data used in this research.

References

1. Hurricane Irma". The Hill. Retrieved September 4, 2017.
2. Marshall, A. | 4 Maps That Show the Gigantic Hurricane Irma Evacuation. [Online].
3. Jansen, Bart. "Timeline: Hurricane Irma's Progress to Monster Storm." USA Today, 602 Gannett Satellite Information Network, 10 Sept. 2017, 603 www.usatoday.com/story/news/2017/09/10/timeline-hurricane-irma-fluctuating-604strgrowing-stronger-weaker-crashed-into-caribbean-islands-florid/651421001
4. O'Connor, Amy. "Florida's Hurricane Irma Recovery: The Cost, The Challenges, The Lessons." Insurance Journal, 4 Dec. 2017
5. Associated Press. "Curfew Lifted in Florida Keys 3 Weeks After Hurricane Irma." U.S. News & World Report, U.S. News & World Report, 2 Oct. 2017, www.usnews.com/news/best-states/florida/articles/2017-10-02/curfew-lifted-in-florida-keys-3-weeks-after-hurricane-irma.
6. Noaa.gov. [cited 2020 Jun 29]. Available from:https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf
7. Murray-Tuite, P., Lindell, M. K., Wolshon, B., & Baker, E. J. (2018). Large-scale evacuation: The analysis, modeling, and management of emergency relocation from hazardous areas. CRC Press
8. Shekhar, S., Yang, K., Gunturi, V. M., Manikonda, L., Oliver, D., Zhou, X., ... & Lu, Q. (2012). Experiences with evacuation route planning algorithms. International Journal of Geographical Information Science, 26(12), 2253-2265
9. Meyer MD, McLeod S, Fidell T, Gajjar H, Sood D, Kamali M, Wingate R, Willauer DO, Southworth F. Freight Transportation Resilience in Response to Supply Chain Disruptions. 2019.
10. Chang SE, Nojima N. Measuring post-disaster transportation system performance: the 1995 Kobe earthquake in comparative perspective. Transportation research part A: policy and practice. 2001 Jul 1;35(6):475-94.
11. Wolshon, B., Empirical Characterization of Mass Evacuation Traffic Flow. Transportation Research Record: Journal of the Transportation Research Board, 2008(2041): p. pp 38-48.
12. Wolshon B, McArdle B. Temporospatial analysis of Hurricane Katrina regional evacuation traffic patterns. Journal of Infrastructure Systems. 2009 Mar;15(1):12-20.
13. Archibald E, McNeil S. Learning from traffic data collected before, during and after a hurricane. IATSS research. 2012 Jul 1;36(1):1-0.
14. Li, J., K. Ozbay, B. Bartin, S. Iyer, and J.A. Carnegie, Empirical evacuation response curve during hurricane Irene in Cape May County, New Jersey. Transportation Research Record, 2013
15. U.S. Department of Transportation, Federal Highway Administration. Traffic Monitoring Guide. Washington D.C. 2016
16. Lindell, M. K., Murray-Tuite, P., Wolshon, B., & Baker, E. J. (2019). Large-Scale Evacuation: The Analysis, Modeling, and Management of Emergency Relocation from Hazardous Areas. New York: Taylor and Francis.